PAUL SCHERRER INSTITUT

HIGGS COUPLINGS – THEORY

Michael Spira (PSI)

I Introduction

II Effective Lagrangians

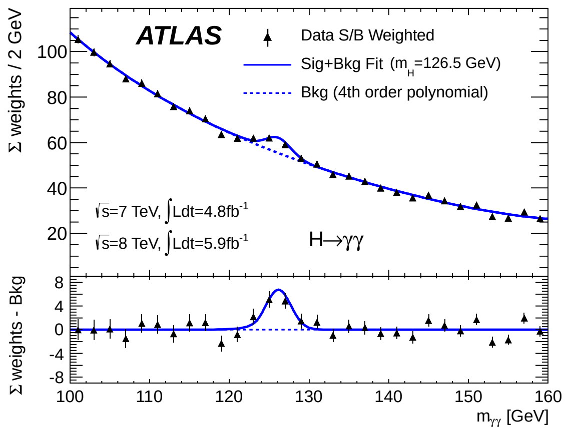
III BSM Models

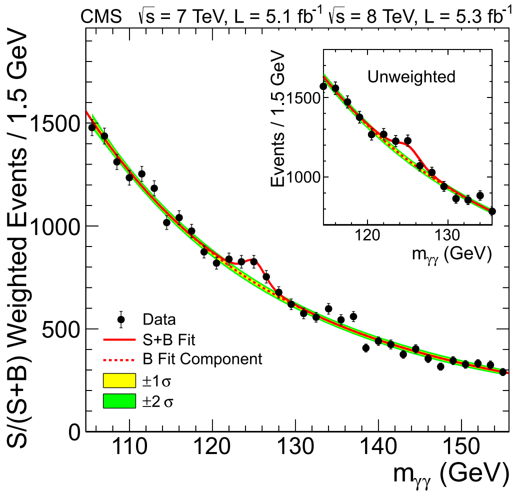
IV Conclusions

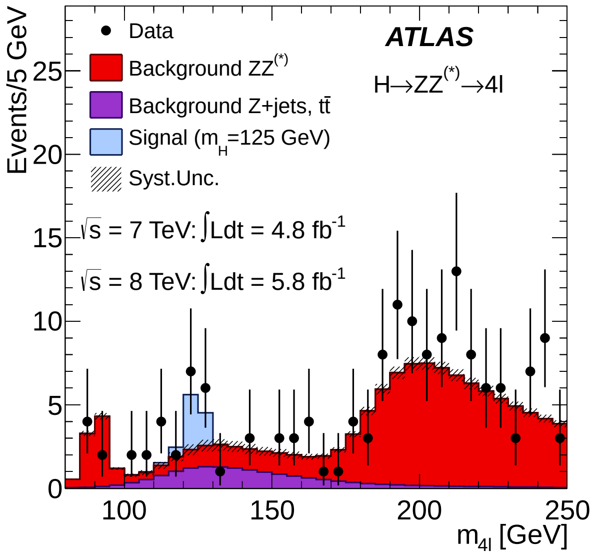
I INTRODUCTION

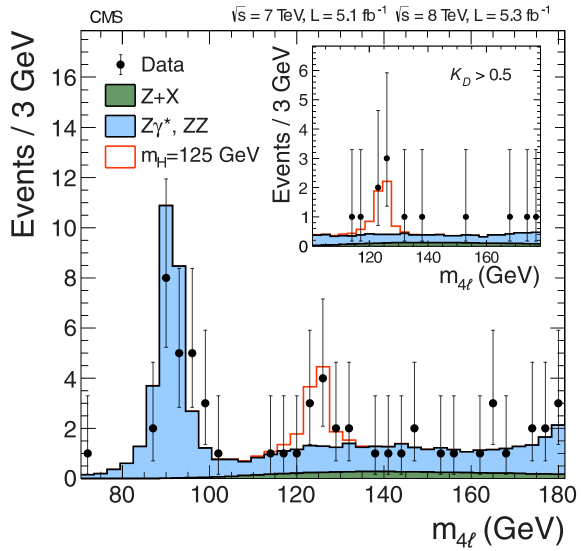
(i) Standard Model

- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \to H$ dominant

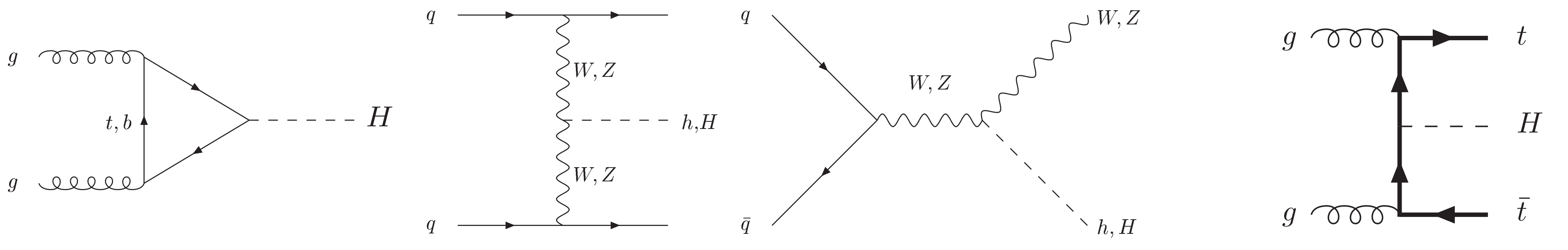


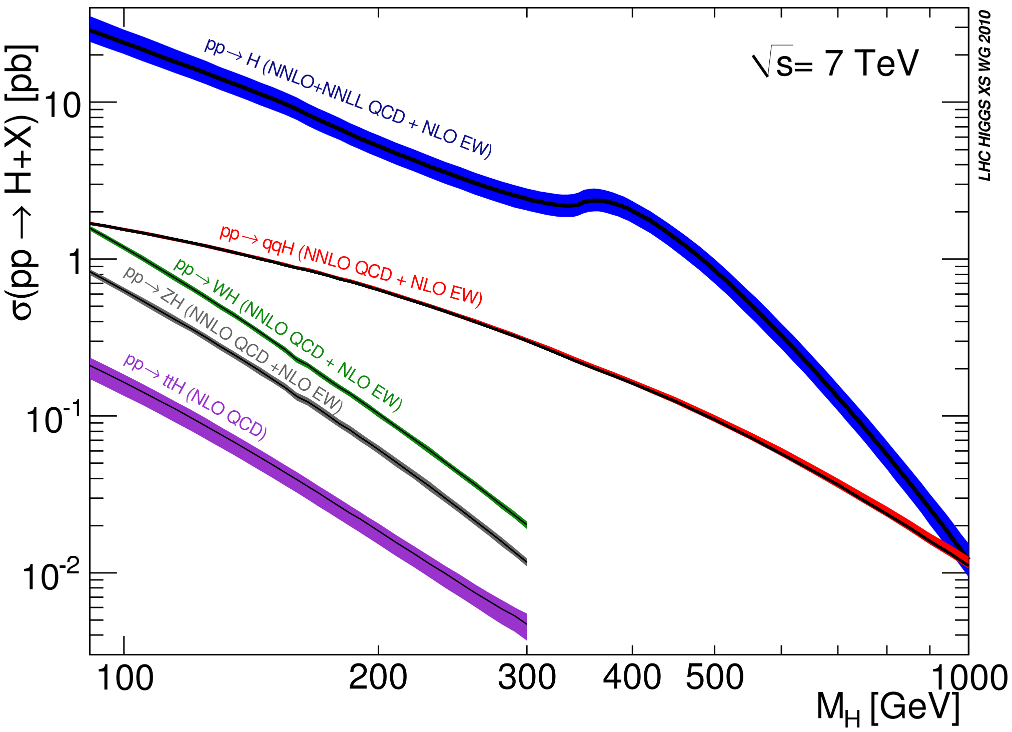


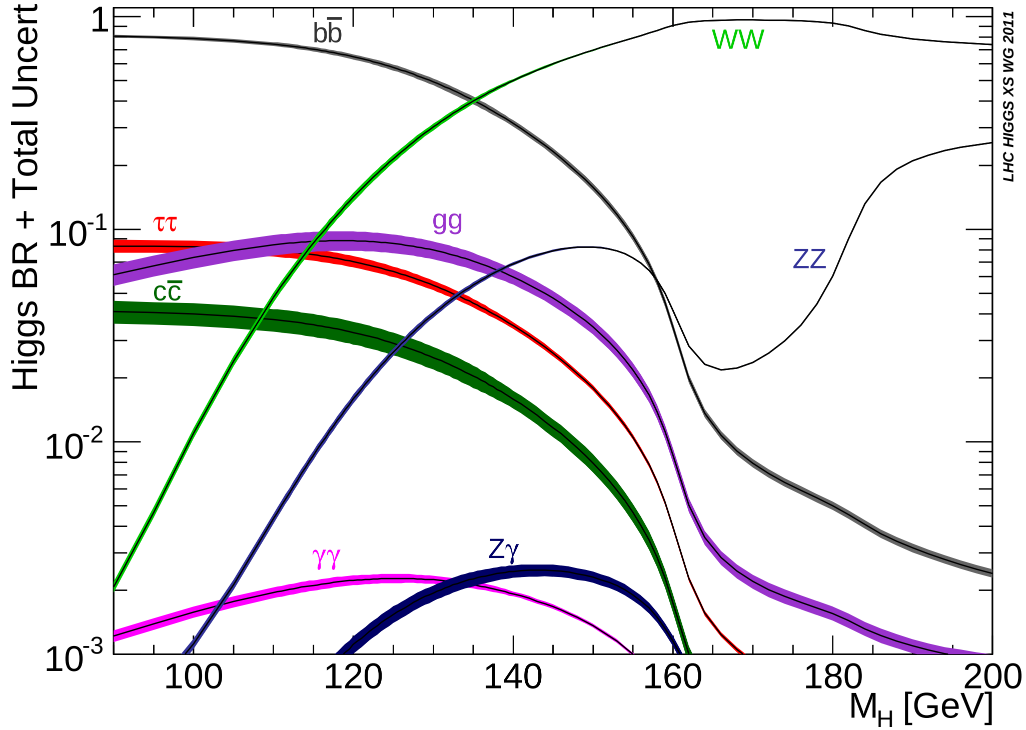




- Higgs Boson Production

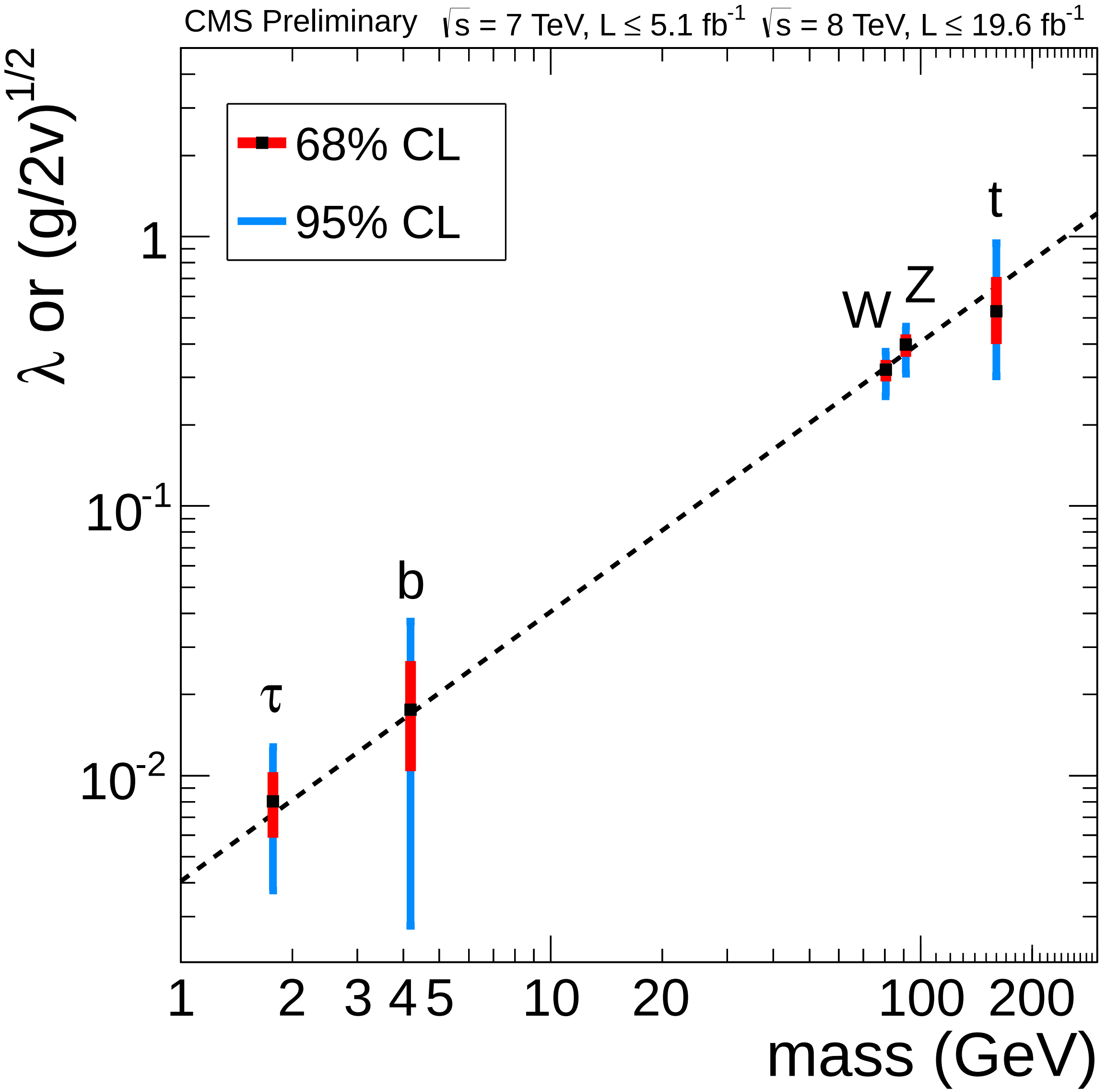






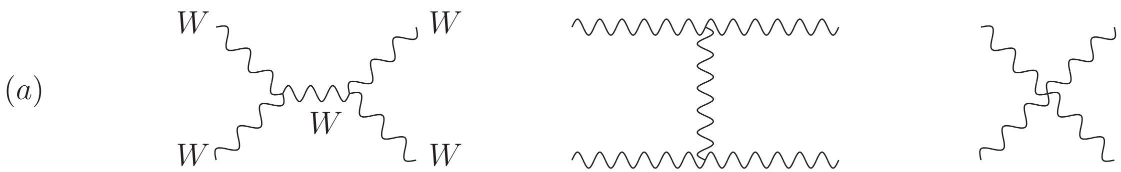
LHC Higgs XS WG

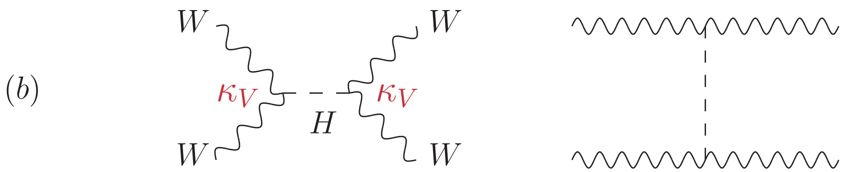
- Discovery: LHC [Tevatron]
  $\rightarrow$ Higgs mass
  couplings
  spin
  $\mathcal{CP}$
  λ ?



CMS

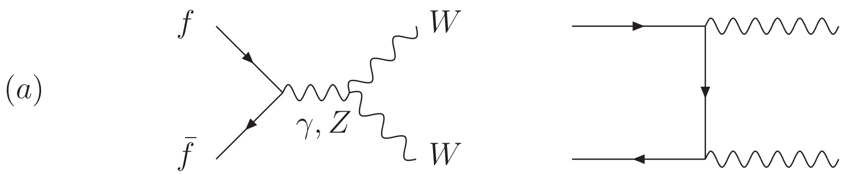
- $WW \to WW$ @ high energies

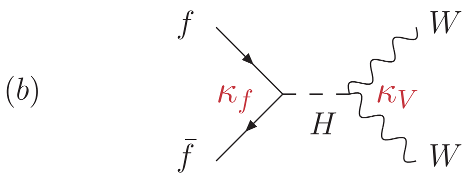




$$\mathcal{A} = \frac{s}{v^2}\left\{1 - \frac{\kappa_V^2 s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_V = 1$$

- $f\bar{f} \to WW$ @ high energies





$$\mathcal{A} = \frac{m_f\sqrt{s}}{v^2}\left\{1 - \frac{\kappa_f \kappa_V s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_f = \kappa_V = 1$$

- analogously for κ_H

- modifications: (i) higher-dim. operators $\to$ eff. Lagrangians
  (ii) extended Higgs sectors (mixing, loop effects)

II EFFECTIVE LAGRANGIANS

(i) weakly interacting theories

• effective higher dimension operators up to dim 6

Burges, Schnitzer
Leung, Love, Rao
Buchmüller, Wyler
Grzadkowski, Iskrzynski, Misiak, Rosiek
Giudice, Grojean, Pomarol, Rattazzi

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i \\ &\equiv \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \\ &\equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2} + \Delta\mathcal{L}_{bos} + \Delta\mathcal{L}_{4f} + \Delta\mathcal{L}_{\mathcal{CP}}\end{aligned}$$

[assume Λ large]

• assume Higgs $SU(2)$-doublet

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} \;=\;& \frac{\bar{c}_H}{2v^2}\,\partial^\mu\Big(H^\dagger H\Big)\,\partial_\mu\Big(H^\dagger H\Big) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) - \frac{\bar{c}_6\,\lambda}{v^2}\Big(H^\dagger H\Big)^3 \\
&+ \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
&+ \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger\overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
&+ \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
&+ \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
\Delta\mathcal{L}_{F_1} \;=\;& \frac{i\bar{c}_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu q_L)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}'_{Hq}}{v^2}\Big(\bar{q}_L\gamma^\mu\sigma^i q_L\Big)\Big(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\Big) \\
&+ \frac{i\bar{c}_{Hu}}{v^2}\,(\bar{u}_R\gamma^\mu u_R)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}_{Hd}}{v^2}\Big(\bar{d}_R\gamma^\mu d_R\Big)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) \\
&+ \left(\frac{i\bar{c}_{Hud}}{v^2}\,(\bar{u}_R\gamma^\mu d_R)\Big(H^{c\,\dagger}\overleftrightarrow{D}_\mu H\Big) + h.c.\right) \\
&+ \frac{i\bar{c}_{HL}}{v^2}\Big(\bar{L}_L\gamma^\mu L_L\Big)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}'_{HL}}{v^2}\Big(\bar{L}_L\gamma^\mu\sigma^i L_L\Big)\Big(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\Big) \\
&+ \frac{i\bar{c}_{Hl}}{v^2}\Big(\bar{l}_R\gamma^\mu l_R\Big)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) \\
\Delta\mathcal{L}_{F_2} \;=\;& \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu} \\
&+ \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu} \\
&+ \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_{bos} &= \frac{\bar{c}_{3W}\,g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\,g_S^3}{m_W^2}\,f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}G_\rho^{c\,\mu} \\
&+ \frac{\bar{c}_{2W}}{m_W^2}\,(D^\mu W_{\mu\nu})^i\,(D_\rho W^{\rho\nu})^i + \frac{\bar{c}_{2B}}{m_W^2}\,(\partial^\mu B_{\mu\nu})\,(\partial_\rho B^{\rho\nu}) + \frac{\bar{c}_{2G}}{m_W^2}\,(D^\mu G_{\mu\nu})^a\,(D_\rho G^{\rho\nu})^a \\
\Delta\mathcal{L}_{4f} &= \sum_{\psi,L/R,T^a} \bar{\psi}_i\gamma^\mu T^a\psi_j\bar{\psi}_k\gamma_\mu T^a\psi_l + \bar{\psi}_i T^a\psi_j\bar{\psi}_k T^a\psi_l \\
\Delta\mathcal{L}_{\mathcal{CP}} &= \frac{i\tilde{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)\tilde{W}_{\mu\nu}^i + \frac{i\tilde{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)\tilde{B}_{\mu\nu} \\
&+\frac{\tilde{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G_{\mu\nu}^a\tilde{G}^{a\mu\nu} \\
&+\frac{\tilde{c}_{3W}\,g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}\tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\,g_S^3}{m_W^2}\,f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}\tilde{G}_\rho^{c\,\mu}
\end{aligned}
$$

$$
\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}V^{\alpha\beta}
$$

- after using EOM: 53 (59) independent dim6 operators $\rightarrow$ different bases

- classification: $[\Phi = H,\ \tilde{\Phi} = i\sigma^2\Phi^*]$

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_{\Phi} = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi} = (\Phi^\dagger\Phi)(\bar{\ell}\,\Gamma_e e\Phi)$	$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_u u\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi} = (\Phi^\dagger\Phi)(\bar{q}\,\Gamma_d d\Phi)$	$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{W}} = \varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{uG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_u u\widetilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\ell}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{\ell}\gamma^\mu\ell)$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi)\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{dG} = (\bar{q}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_d d\Phi) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\ell}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{\ell}\gamma^\mu\tau^I\ell)$
$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eW} = (\bar{\ell}\sigma^{\mu\nu}\Gamma_e e\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\tau^I\widetilde{\Phi}) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\tau^I\Phi) W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{eB} = (\bar{\ell}\sigma^{\mu\nu}\Gamma_e e\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi u} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi) W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}\Gamma_u u\widetilde{\Phi}) B_{\mu\nu}$	$\mathcal{O}_{\Phi d} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}\Gamma_d d\Phi) B_{\mu\nu}$	$\mathcal{O}_{\Phi ud} = i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}\gamma^\mu\Gamma_{ud} d)$

- power counting: $H \to \mathcal{O}(g_*/M = 1/f)$, $\partial_\mu \to \mathcal{O}(1/M)$

$\Rightarrow$ expansion in H/f and E/M

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

Giudice, Grojean, Pomarol, Rattazzi

- canonical normalization, unitary gauge:

$$\begin{aligned} v^2 &= v_{SM}^2 \left(1 + \frac{3}{4}\bar{c}_6\right) \\ h_{SM} &= h\left[1 - \frac{\bar{c}_H}{2} - \frac{\bar{c}_T}{8}\right] - \frac{3}{8}\bar{c}_6 v \\ m_h^2 &= m_{h_{SM}}^2 \left[1 - \bar{c}_H + \frac{3}{2}\bar{c}_6 - \frac{1}{2}\bar{c}_T\right] \end{aligned}$$

$etc.$

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\ \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \frac{h}{v} + \ldots\right)$$
$$+ m_W^2\, W_\mu W^\mu \left(1 + 2c_W \frac{h}{v} + \ldots\right) + \frac{1}{2} m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z \frac{h}{v} + \ldots\right) + \ldots$$
$$+ \left(c_{WW}\, W^+_{\mu\nu} W^{-\mu\nu} + \frac{c_{ZZ}}{2} Z_{\mu\nu} Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2} G^a_{\mu\nu} G^{a\mu\nu}\right)\frac{h}{v}$$
$$+ \left(c_{W\partial W}\left(W^-_\nu D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\frac{h}{v} + \ldots$$

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
c_W	$1 - \bar{c}_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
c_Z	$1 - \bar{c}_H/2 - 2\bar{c}_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$c_\psi\ \ (\psi = u,d,l)$	$1 - (\bar{c}_H/2 + \bar{c}_\psi)$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_3	$1 + \bar{c}_6 - 3\bar{c}_H/2$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_{gg}	$8\,(\alpha_s/\alpha_2)\,\bar{c}_g$	0	0
$c_{\gamma\gamma}$	$8\sin^2\theta_W\,\bar{c}_\gamma$	0	0
$c_{Z\gamma}$	$\left(\bar{c}_{HB} - \bar{c}_{HW} - 8\,\bar{c}_\gamma \sin^2\theta_W\right)\tan\theta_W$	0	0
c_{WW}	$-2\,\bar{c}_{HW}$	0	0
c_{ZZ}	$-2\left(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W - 4\bar{c}_\gamma \tan^2\theta_W \sin^2\theta_W\right)$	0	0
$c_{W\partial W}$	$-2(\bar{c}_W + \bar{c}_{HW})$	0	0
$c_{Z\partial Z}$	$-2(\bar{c}_W + \bar{c}_{HW}) - 2\,(\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W$	0	0
$c_{Z\partial\gamma}$	$2\,(\bar{c}_B + \bar{c}_{HB} - \bar{c}_W - \bar{c}_{HW})\tan\theta_W$	0	0

small deviations from SM couplings

8 operators relevant for Higgs physics

Contino, Ghezzi, Grojean, Mühlleitner, S.

- constraints from precision measurements:

$$\Delta\epsilon_1 \equiv \Delta\rho = \bar{c}_T(m_Z), \qquad -1.5\times 10^{-3} < \bar{c}_T(m_Z) < 2.2\times 10^{-3}$$

$$\Delta\epsilon_3 = \bar{c}_W(m_Z) + \bar{c}_B(m_Z)\,, \qquad -1.4\times 10^{-3} < \bar{c}_W(m_Z) + \bar{c}_B(m_Z) < 1.9\times 10^{-3}$$

- Z-pole measurements:

$$\frac{\delta g_{L\psi}}{g_{L\psi}} = \frac{1}{2}\,\frac{\bar{c}_{H\Psi} + 2\,T_{3L}\,\bar{c}'_{H\Psi}}{T_{3L} - Q\sin^2\theta_W}\,, \qquad \frac{\delta g_{R\psi}}{g_{R\psi}} = \frac{1}{2}\,\frac{\bar{c}_{H\psi}}{Q\sin^2\theta_W}$$

$$-0.03 < \bar{c}_{Hq1} < 0.02\,, \quad -0.002 < \bar{c}'_{Hq1} < 0.003\,,$$

$$-0.005 < \bar{c}_{Hq2} < 0.003\,, \quad -0.003 < \bar{c}'_{Hq2} < 0.005\,,$$

$$-0.008 < \bar{c}_{Hu} < 0.02\,, \quad -0.03 < \bar{c}_{Hd} < 0.02\,, \quad -0.03 < \bar{c}_{Hs} < 0.02$$

$$-0.004 < \bar{c}_{HL} + \bar{c}'_{HL} < 0.002\,, \quad -0.003 < \bar{c}_{HL} - \bar{c}'_{HL} < 0.0002\,, \quad -0.0007 < \bar{c}_{Hl} < 0.003\,,$$

$$-0.02 < \bar{c}_{Hq_2} + \bar{c}'_{Hq_2} < 0.005\,, \quad -0.02 < \bar{c}_{Hc} < 0.03\,,$$

$$-0.003 < \bar{c}_{Hq_3} - \bar{c}'_{Hq_3} < 0.009\,, \quad -0.07 < \bar{c}_{Hb} < -0.005$$

- EDMs: neutron & mercury:

$$-7.01 \times 10^{-6} < \mathrm{Im}(\bar{c}_{uB} + \bar{c}_{uW}) < 7.86 \times 10^{-6}\,,$$

$$-9.42 \times 10^{-7} < \mathrm{Im}(\bar{c}_{dB} - \bar{c}_{dW}) < 8.40 \times 10^{-7}\,,$$

$$-1.62 \times 10^{-6} < \mathrm{Im}(\bar{c}_{uG}) < 2.01 \times 10^{-6}\,,$$

$$-7.71 \times 10^{-7} < \mathrm{Im}(\bar{c}_{dG}) < 5.70 \times 10^{-7}\,,$$

- top quark: nEDM, $b \to s\gamma, s\ell^+\ell^-$:

$$-1.39 \times 10^{-4} < \mathrm{Im}(\bar{c}_{tG}) < 1.21 \times 10^{-4}$$
$$-0.057 < \mathrm{Re}(\bar{c}_{tW} + \bar{c}_{tB}) - 2.65\,\mathrm{Im}(\bar{c}_{tW} + \bar{c}_{tB}) < 0.20$$

$t\bar{t}$ cxns @ Tevatron & LHC:

$$-6.12 \times 10^{-3} < \mathrm{Re}(\bar{c}_{tG}) < 1.94 \times 10^{-3}$$
$$-1.2 < \mathrm{Re}(\bar{c}_{bW}) < 1.1\,, \qquad -0.01 < \mathrm{Re}(\bar{c}_{tW}) < 0.02$$

- leptons: EDMs & anomalous magnetic moments:

$$-1.64 \times 10^{-2} < \mathrm{Re}(\bar{c}_{eB} - \bar{c}_{eW}) < 3.37 \times 10^{-3}\,,$$

$$1.88 \times 10^{-4} < \mathrm{Re}(\bar{c}_{\mu B} - \bar{c}_{\mu W}) < 6.43 \times 10^{-4}\,,$$

$$-2.97 \times 10^{-7} < \mathrm{Im}(\bar{c}_{eB} - \bar{c}_{eW}) < 4.51 \times 10^{-7}\,,$$

$$-0.26 < \mathrm{Im}(\bar{c}_{\mu B} - \bar{c}_{\mu W}) < 0.29\,,$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\ \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \frac{h}{v} + \dots\right)$$
$$+ m_W^2\, W_\mu W^\mu \left(1 + 2c_W \frac{h}{v} + \dots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z \frac{h}{v} + \dots\right) + \dots$$
$$+ \left(c_{WW}\, W_{\mu\nu}^+ W^{-\mu\nu} + \frac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}\, G^a_{\mu\nu}G^{a\mu\nu}\right)\frac{h}{v}$$
$$+ \Big(c_{W\partial W}\left(W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu\partial_\mu\gamma^{\mu\nu}\Big)\frac{h}{v} + \dots$$

• also valid in case of a non-linear Lagrangian for a light Higgs-like scalar [h generic $\mathcal{CP}$-even scalar]

$\Rightarrow$ expansion in E/M (derivatives) only, large deviations from SM couplings $\rightarrow \Delta c_i > \frac{\alpha}{\pi}$

SILH: expansion in $v^2/f^2, E^2/M^2, \alpha_s/\pi, \alpha/\pi$

non-lin.: expansion in $E^2/M^2, \alpha_s/\pi$

• how to include state-of-the-art calculations?

e.g. eHDECAY http://www.itp.kit.edu/~maggie/eHDECAY/

• $h \to f\bar{f}$:

$$\Gamma(\bar{\psi}\psi)\big|_{SILH} = \Gamma_0^{SM}(\bar{\psi}\psi)\left[1 - \bar{c}_H - 2\bar{c}_\psi + \frac{2}{|A_0^{SM}|^2}\mathrm{Re}\left(A_0^{*SM} A_{1,ew}^{SM}\right)\right]\left[1 + \delta_\psi\,\kappa^{QCD}\right]$$

$$\Gamma(\bar{\psi}\psi)\big|_{NL} = c_\psi^2\,\Gamma_0^{SM}(\bar{\psi}\psi)\left[1 + \delta_\psi\,\kappa^{QCD}\right]$$

A_0^{SM}: SM tree-level amplitude
$A_{1,ew}^{SM}$: SM elw. amplitude [real corrections treated analogously]

• factorization of QCD $\leftrightarrow$ elw. [limit small m_h]

• NL: no elw. corrections!

- $h \to gg$:

$$\Gamma(gg)\big|_{SILH} = \frac{G_F \alpha_s^2 m_h^3}{4\sqrt{2}\pi^3}\left[\frac{1}{9}\sum_{q,q'=t,b,c}(1-\bar{c}_H-\bar{c}_q-\bar{c}_{q'})\,A^*_{1/2}(\tau_{q'})\,A_{1/2}(\tau_q)\;c^2_{eff}\,\kappa_{soft}\right.$$
$$+2\,\mathrm{Re}\left(\sum_{q=t,b,c}\frac{1}{3}A^*_{1/2}(\tau_q)\,\frac{16\pi\,\bar{c}_g}{\alpha_2}\right)\,c_{eff}\,\kappa_{soft}$$
$$+\left|\sum_{q=t,b,c}\frac{1}{3}A_{1/2}(\tau_q)\right|^2 c^2_{eff}\,\kappa_{ew}\,\kappa_{soft}$$
$$\left.+\frac{1}{9}\sum_{q,q'=t,b}(1-\bar{c}_H-\bar{c}_q-\bar{c}_{q'})A^*_{1/2}(\tau_q)\,A_{1/2}(\tau_{q'})\,\kappa^{NLO}(\tau_q,\tau_{q'})\right]$$

$$\Gamma(gg)\big|_{NL} = \frac{G_F \alpha_s^2 m_h^3}{4\sqrt{2}\pi^3}\left[\left|\sum_{q=t,b,c}\frac{c_q}{3}A_{1/2}(\tau_q)\right|^2 c^2_{eff}\,\kappa_{soft}\right.$$
$$+2\,\mathrm{Re}\left(\sum_{q=t,b,c}\frac{c_q}{3}A^*_{1/2}(\tau_q)\,\frac{2\pi c_{gg}}{\alpha_s}\right)\,c_{eff}\,\kappa_{soft}+\left|\frac{2\pi c_{gg}}{\alpha_s}\right|^2\kappa_{soft}$$
$$\left.+\frac{1}{9}\sum_{q,q'=t,b}c_q\,A^*_{1/2}(\tau_q)\,c_{q'}\,A_{1/2}(\tau_{q'})\,\kappa^{NLO}(\tau_q,\tau_{q'})\right]$$

$$
\begin{aligned}
A_{1/2}(\tau) &= \frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right] \\
f(\tau) &= \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4}\left[\ln\dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1\,. \end{cases}
\end{aligned}
$$

$$
\kappa_{soft}^{NLO} = 1 + \frac{\alpha_s}{\pi}\left(\frac{73}{4} - \frac{7}{6}N_F\right) + \mathcal{O}(\alpha_s^2)\,, \qquad c_{eff}^{NLO} = 1 + \frac{\alpha_s}{\pi}\frac{11}{4} + \mathcal{O}(\alpha_s^2)
$$

Inami, Kubota, Okada
Djouadi, S., Zerwas
Chetyrkin, Kniehl, Steinhauser
Krämer, Laenen, S.
Baikov, Chetyrkin

- $\kappa^{NLO}(\tau_q, \tau_{q'})$: NLO mass effects ($\lesssim$ 5% in SM)

- $h \to \gamma\gamma$:

$$\Gamma(\gamma\gamma)\big|_{SILH} = \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3}\Bigg\{ |A_{NLO}^{SM}(\gamma\gamma)|^2 + 2\,\mathrm{Re}\Big(A_{LO}^{SM*}(\gamma\gamma)\, A_{ew}^{SM}(\gamma\gamma)\Big) + 2\,\mathrm{Re}\Big[A_{NLO}^{SM*}(\gamma\gamma)\left(\Delta A(\gamma\gamma) + \frac{32\pi \sin^2\theta_W\, \bar{c}_\gamma}{\alpha_{em}}\right)\Big]\Bigg\}$$

$$\Gamma(\gamma\gamma)\big|_{NL} = \frac{G_F \alpha_{em}^2 m_h^3}{128\sqrt{2}\pi^3}\left| \sum_{q=t,b,c} \frac{4}{3} c_q\, 3Q_q^2\, A_{1/2}^{NLO}(\tau_q) + \frac{4}{3} c_\tau Q_\tau^2 A_{1/2}(\tau_\tau) + c_V A_1(\tau_W) + \frac{4\pi}{\alpha_{em}} c_{\gamma\gamma} \right|^2$$

$$\Delta A(\gamma\gamma) = -\sum_{q=t,b,c} \frac{4}{3}\left(\frac{\bar{c}_H}{2} + \bar{c}_q\right) 3Q_q^2\, A_{1/2}^{NLO}(\tau_q) - \left(\frac{\bar{c}_H}{2} + \bar{c}_\tau\right)\frac{4}{3} Q_\tau^2\, A_{1/2}(\tau_\tau) - \left(\frac{\bar{c}_H}{2} - 2\bar{c}_W\right) A_1(\tau_W)$$

$$A_1(\tau) = -\left[2 + 3\tau + 3\tau(2-\tau) f(\tau)\right]$$

$$A_{1/2}^{NLO}(\tau_q) = A_{1/2}(\tau_q)(1 + \kappa_{QCD})$$

- κ_{QCD}: massive QCD corrections

Djouadi, S., Zerwas
Melnikov, Yakovlev
Inoue, Najima, Oka, Saito

- $h \to Z\gamma$:

$$
\begin{aligned}
\Gamma(Z\gamma)\Big|_{SILH} &= \frac{G_F^2 \alpha_{em} m_W^2 m_h^3}{64\pi^4}\left(1-\frac{m_Z^2}{m_h^2}\right)^3 \\
&\times \Bigg\{ \left|A^{SM}(Z\gamma)\right|^2 + 2\,\mathrm{Re}\Big(A^{SM*}(Z\gamma)\,\Delta A(Z\gamma)\Big) \\
&\quad +2\,\mathrm{Re}\left[-\frac{4\pi\tan\theta_W}{\sqrt{\alpha_{em}\alpha_2}}(\bar{c}_{HB}-\bar{c}_{HW}-8\bar{c}_\gamma\sin^2\theta_W)\,A^{SM*}(Z\gamma)\right]\Bigg\} \\
\Gamma(Z\gamma)\Big|_{NL} &= \frac{G_F^2 \alpha_{em} m_W^2 m_h^3}{64\pi^4}\left(1-\frac{m_Z^2}{m_h^2}\right)^3 \\
&\times \left|\sum_\psi \frac{c_\psi N_c Q_\psi \hat{v}_\psi}{\cos\theta_W} A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) + c_V\, A_1^{Z\gamma}(\tau_W,\lambda_W) - \frac{4\pi}{\sqrt{\alpha_{em}\alpha_2}}\,c_{Z\gamma}\right|^2 \\
A_{1/2}^{Z\gamma}(\tau,\lambda) &= \left[I_1(\tau,\lambda) - I_2(\tau,\lambda)\right] \\
A_1^{Z\gamma}(\tau,\lambda) &= \cos\theta_W\Bigg\{4\Big(3-\tan^2\theta_W\Big)I_2\Big(\tau,\lambda\Big) \\
&\quad +\left[\left(1+\frac{2}{\tau}\right)\tan^2\theta_W - \left(5+\frac{2}{\tau}\right)\right]I_1\Big(\tau,\lambda\Big)\Bigg\} \\
\Delta A(Z\gamma) &= -\sum_\psi\left(\frac{\bar{c}_H}{2}+\bar{c}_\psi\right)\frac{N_c Q_\psi \hat{v}_\psi}{\cos\theta_W} A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) - \left(\frac{\bar{c}_H}{2} - 2\bar{c}_W\right) A_1^{Z\gamma}(\tau_W,\lambda_W) \\
A^{SM}(Z\gamma) &= \sum_\psi \frac{N_c Q_\psi \hat{v}_\psi}{\cos\theta_W} A_{1/2}^{Z\gamma}\left(\tau_\psi,\lambda_\psi\right) + A_1^{Z\gamma}(\tau_W,\lambda_W)
\end{aligned}
$$

$$
\begin{aligned}
I_1(\tau,\lambda) &= \frac{\tau\lambda}{2(\tau-\lambda)} + \frac{\tau^2\lambda^2}{2(\tau-\lambda)^2}\left[f(\tau)-f(\lambda)\right] + \frac{\tau^2\lambda}{(\tau-\lambda)^2}\left[g(\tau)-g(\lambda)\right] \\
I_2(\tau,\lambda) &= -\frac{\tau\lambda}{2(\tau-\lambda)}\left[f(\tau)-f(\lambda)\right] \\
g(\tau) &= \begin{cases} \sqrt{\tau-1}\,\arcsin\dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ \dfrac{\sqrt{1-\tau}}{2}\left[\ln\dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right] & \tau < 1\,. \end{cases}
\end{aligned}
$$

- $h \to Z^*Z^*, W^*W^*$:

$$\Gamma(V^*V^*) = \frac{1}{\pi^2}\int_0^{m_h^2} \frac{dQ_1^2\, m_V\Gamma_V}{\left(Q_1^2 - m_V^2\right)^2 + m_V^2\Gamma_V^2} \int_0^{(m_h-Q_1)^2} \frac{dQ_2^2\, m_V\Gamma_V}{\left(Q_2^2 - m_V^2\right)^2 + m_V^2\Gamma_V^2}\, \Gamma(VV)$$

$$\Gamma(VV)\Big|_{NL} = \Gamma^{SM}(VV) \times \left\{ c_V^2 - 2c_V \left[\frac{a_{VV}}{2}\left(1 - \frac{Q_1^2+Q_2^2}{m_h^2}\right) + a_{V\partial V}\frac{Q_1^2+Q_2^2}{m_h^2}\right] + c_V a_{VV}\, \frac{\lambda\left(Q_1^2, Q_2^2, m_h^2\right)\ (1-(Q_1^2+Q_2^2)/m_h^2)}{\lambda\left(Q_1^2, Q_2^2, m_h^2\right) + 12\, Q_1^2 Q_2^2/m_h^4} \right\}$$

$$a_{VV} = c_{VV}\,\frac{m_h^2}{m_V^2}\,, \qquad a_{V\partial V} = \frac{c_{V\partial V}}{2}\,\frac{m_h^2}{m_V^2}$$

$$\Gamma(VV)\Big|_{SILH} = \Gamma^{SILH}(VV) + \Gamma^{SM}(VV)\frac{2}{|A_0^{SM}|^2}\,\mathrm{Re}\left(A_0^{*SM} A_{ew}^{SM}\right)$$

$$\Gamma^{SILH}(VV) = \Gamma^{SM}(VV) \times \left\{ 1 - \bar{c}_H - 2\left[\frac{\bar{a}_{VV}}{2}\left(1 - \frac{Q_1^2+Q_2^2}{m_h^2}\right) + \bar{a}_{V\partial V}\frac{Q_1^2+Q_2^2}{m_h^2}\right] + \bar{a}_{VV}\, \frac{\lambda\left(Q_1^2, Q_2^2, m_h^2\right)\ (1-(Q_1^2+Q_2^2)/m_h^2)}{\lambda\left(Q_1^2, Q_2^2, m_h^2\right) + 12\, Q_1^2 Q_2^2/m_h^4} \right\}$$

$$\Gamma^{SM}(VV) = \frac{\delta_V G_F m_h^3}{16\sqrt{2}\pi}\sqrt{\lambda\left(Q_1^2, Q_2^2, m_h^2\right)}\left(\lambda\left(Q_1^2, Q_2^2, m_h^2\right) + \frac{12 Q_1^2 Q_2^2}{m_h^4}\right)$$

$$\bar{a}_{WW} = -2\,\frac{m_h^2}{m_W^2}\,\bar{c}_{HW}\,, \qquad \bar{a}_{ZZ} = -2\,\frac{m_h^2}{m_Z^2}\left(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W - 4\bar{c}_\gamma \tan^2\theta_W \sin^2\theta_W\right)$$

$$\bar{a}_{W\partial W} = -2\,\frac{m_h^2}{2m_W^2}\left(\bar{c}_W + \bar{c}_{HW}\right)\,, \quad \bar{a}_{Z\partial Z} = -2\,\frac{m_h^2}{2m_Z^2}\left(\bar{c}_W + \bar{c}_{HW} + (\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W\right)$$

- approximate formulae [w/o elw. corrections]: $\alpha_2 = \sqrt{2} G_F m_W^2/\pi$

$$\frac{\Gamma(\bar\psi\psi)}{\Gamma(\bar\psi\psi)_{SM}} \simeq 1 - \bar c_H - (2 - x_\psi)\,\bar c_\psi - x_\psi \bar c_t \qquad x_{b,c,s} = 0.0085, 0.015, 0.029$$

$$\frac{\Gamma(h\to W^{(*)}W^*)}{\Gamma(h\to W^{(*)}W^*)_{SM}} \simeq 1 - \bar c_H + 2.2\,\bar c_W + 3.7\,\bar c_{HW}$$

$$\frac{\Gamma(h\to Z^{(*)}Z^*)}{\Gamma(h\to Z^{(*)}Z^*)_{SM}} \simeq 1 - \bar c_H + 2.0\,\left(\bar c_W + \tan^2\theta_W\,\bar c_B\right) + 3.0\,\left(\bar c_{HW} + \tan^2\theta_W\,\bar c_{HB}\right) - 0.26\,\bar c_\gamma$$

$$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}} \simeq 1 - \bar c_H + 0.12\,\bar c_t - 5\cdot 10^{-4}\,\bar c_c - 0.003\,\bar c_b - 9\cdot 10^{-5}\,\bar c_\tau + 4.2\,\bar c_W + 0.19\,\left(\bar c_{HW} - \bar c_{HB} + 8\,\bar c_\gamma \sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}}$$

$$\frac{\Gamma(h\to \gamma\gamma)}{\Gamma(h\to \gamma\gamma)_{SM}} \simeq 1 - \bar c_H + 0.54\,\bar c_t - 0.003\,\bar c_c - 0.007\,\bar c_b - 0.007\,\bar c_\tau + 5.04\,\bar c_W - 0.54\,\bar c_\gamma\,\frac{4\pi}{\alpha_{em}}$$

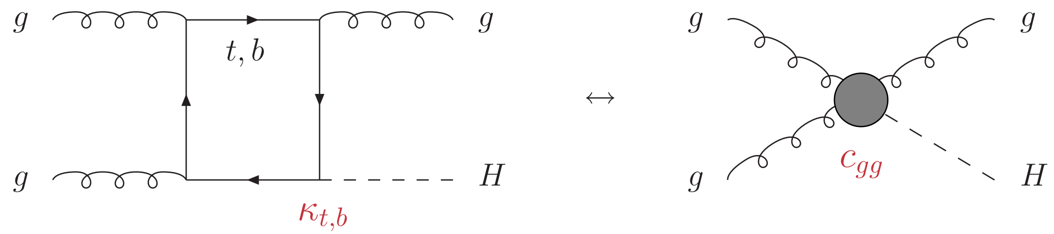
$$\frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{SM}} \simeq 1 - \bar c_H - 2.12\,\bar c_t + 0.024\,\bar c_c + 0.1\,\bar c_b + 22.2\,\bar c_g\,\frac{4\pi}{\alpha_2}$$

← eHDECAY

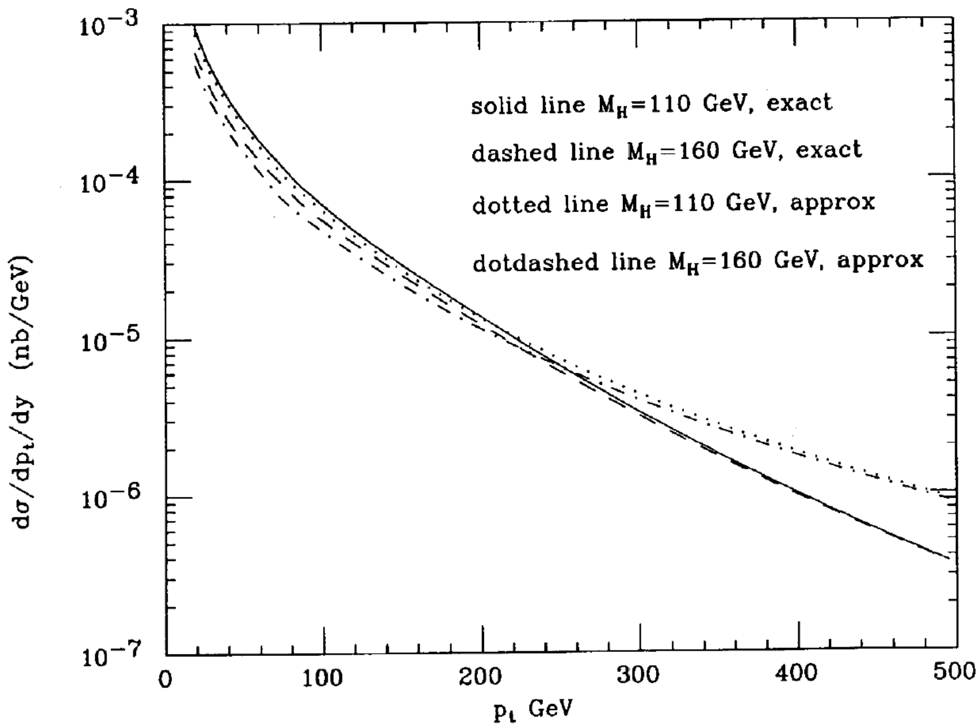
Contino, Ghezzi, Grojean, Mühlleitner, S.

OTHER APPLICATIONS : PRODUCTION

(i) Higgs p_T (or how to prove that ggF is loop-mediated)



- distinction dim4 $\leftrightarrow$ dim5

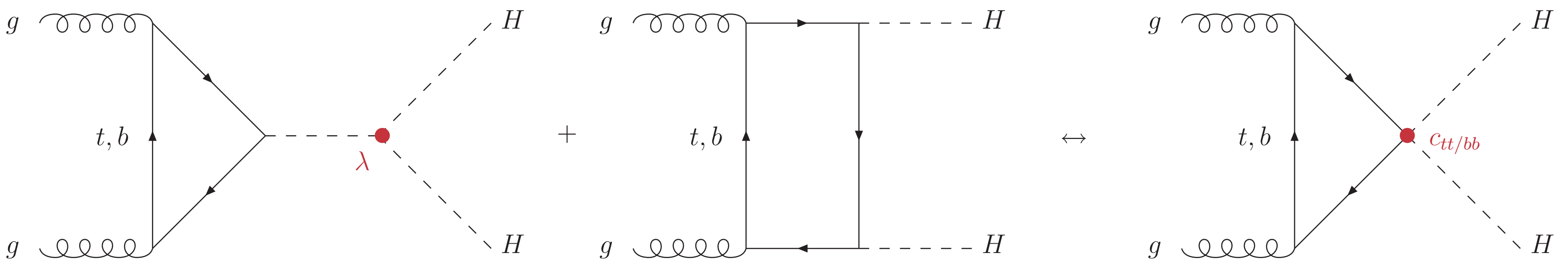


- first studies Banfi, Martin, Sanz
  Azatov, Paul
  Englert, McCullough, Spannowsky
  Grojean, Salvoni, Schlaffer, Weiler

$m_t = 160$ GeV

Ellis, Hinchliffe, Soldate, van der Bij

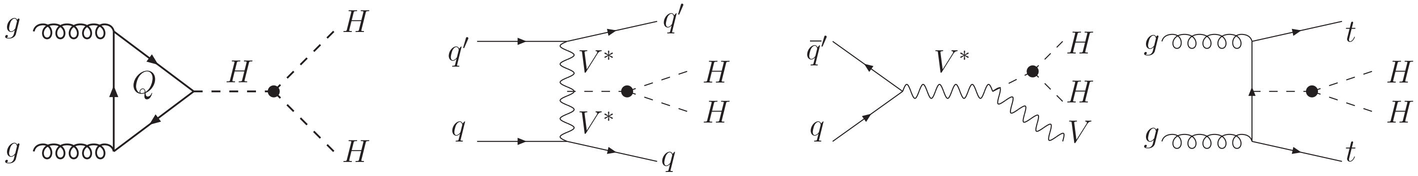
(ii) anomalous Higgs couplings [e.g. composite Higgs]

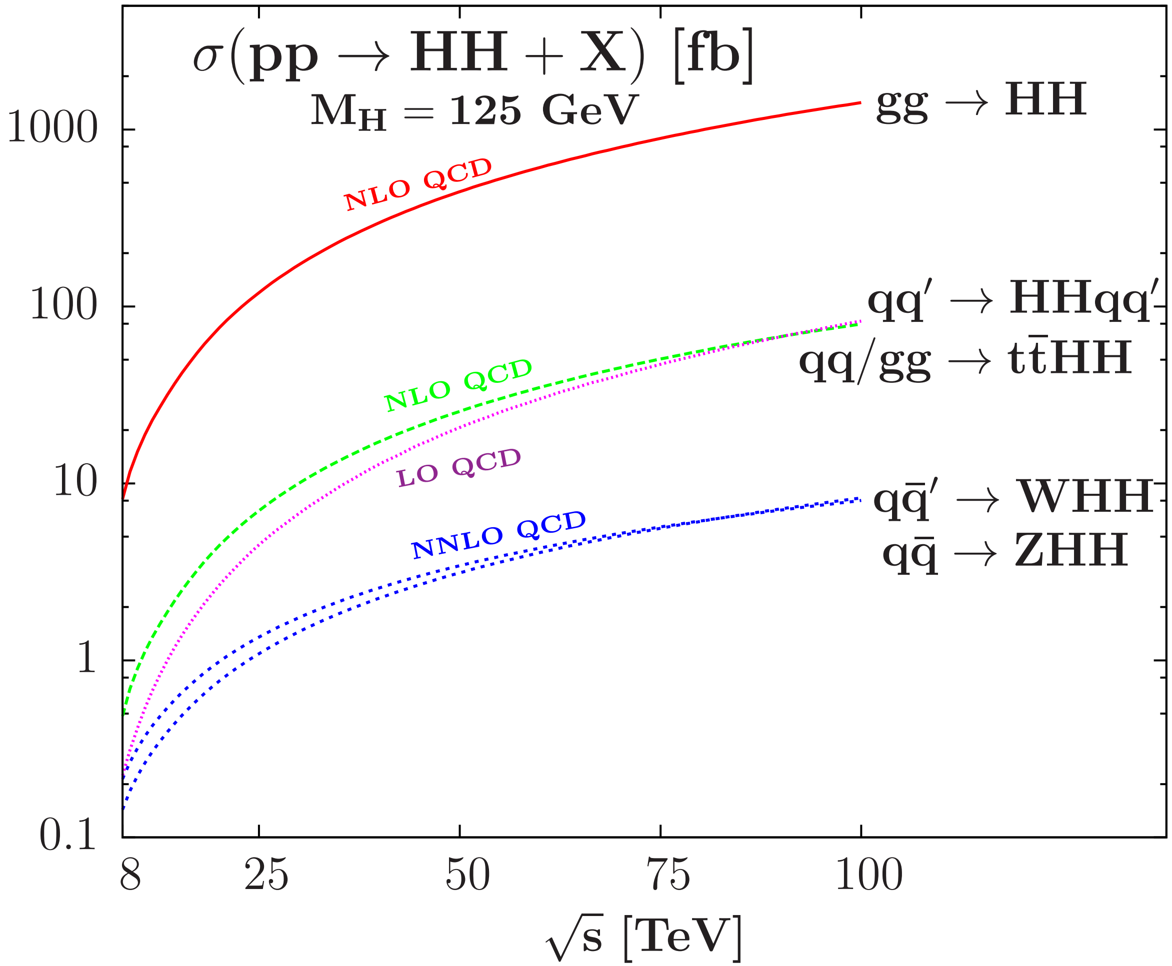


- threshold region: sensitive to λ
  large M_{HH}: sensitive to $c_{tt/bb}$ [e.g. boosted Higgs pairs]

- similar effects for other Higgs pair production modes

- tiny event rates





Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

- $t\bar{t}HH$ @ NLO

Frederix, Frixione, Maltoni, . . .

• simplified scheme [$\leftarrow$ LHC]

rescale SM Higgs couplings $\rightarrow \kappa_f, \kappa_{W/Z}$

rescale SM Higgs couplings to $\gamma\gamma, gg \rightarrow \kappa_\gamma, \kappa_g$ [if not via κ_f, κ_V]

rescale total SM Higgs width $\rightarrow \kappa_H$

include all QCD and elw. corrections [factorized]

e.g. $(\sigma \times BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) BR_{SM}(H \rightarrow \gamma\gamma) \times \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$

$\rightarrow$ A. David

reliable within 10–20%

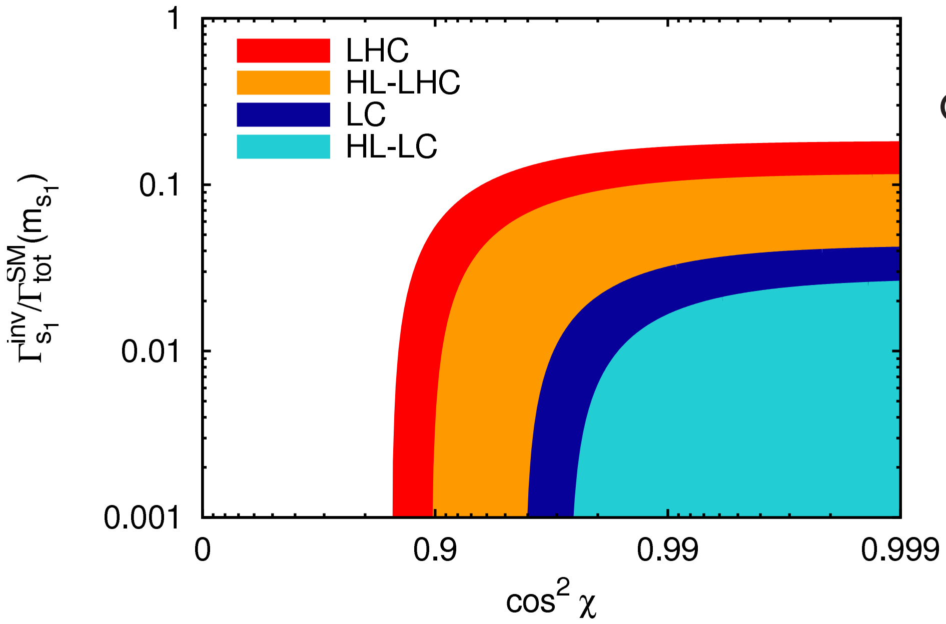
III *BSM MODELS*

(i) Higgs portal models

• dark sector: $\mathcal{L}_{new} = -\mu_s^2|\phi_s|^2 - \mu_d^2|\phi_d|^2 - \frac{\lambda_s}{2}|\phi_s|^4 - \frac{\lambda_d}{2}|\phi_d|^4 - \eta|\phi_s|^2|\phi_d|^2$

$$\mathcal{M}^2 = \begin{pmatrix} \lambda_s v_s^2 & \eta v_s v_d \\ \eta v_s v_d & \lambda_d v_d^2 \end{pmatrix}$$

$\Rightarrow g_s = g_h^{SM} \cos\chi \quad$ with $\quad \tan(2\chi) \simeq -\frac{2\eta\, v_s}{\lambda_d v_d} \quad (v_d \gg v_s)$



decays into inv. light dark fermions $\rightarrow \Gamma_{inv}$

Englert, Freitas, Mühlleitner,. . .

(ii) 2HDM

$$
\begin{aligned}
V &= m_{11}|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + \text{h.c}) + \lambda_1|\phi_1|^4 + \lambda_2|\phi_2|^4 \\
&+ \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \frac{1}{2}\lambda_5[(\phi_1^\dagger\phi_2)^2 + \text{h.c}]
\end{aligned}
$$

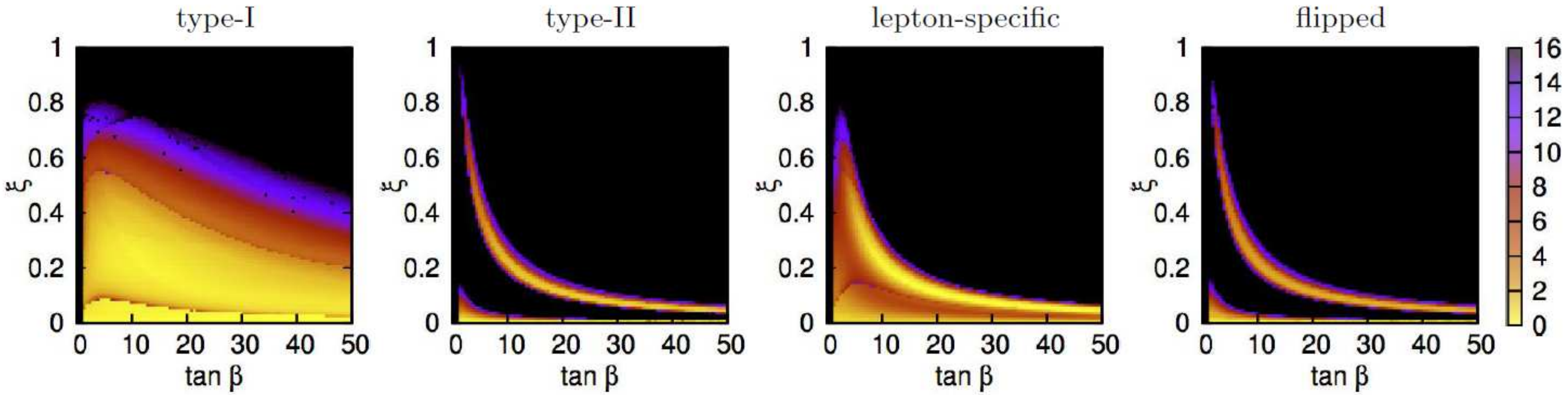
$\frac{\Gamma_{\text{2HDM}}[h \to X]}{\Gamma_{\text{SM}}[h \to X]}$	type I	type II	lepton-spec.	flipped
VV^*	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$	$\sin^2(\beta-\alpha)$
$\bar{u}u$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$
$\bar{d}d$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$
$\ell^+\ell^-$	$\frac{\cos^2\alpha}{\sin^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\sin^2\alpha}{\cos^2\beta}$	$\frac{\cos^2\alpha}{\sin^2\beta}$

- heavy 2nd Higgs doublet $\Rightarrow m_{A,H,H^\pm}^2 = \frac{2m_{12}^2}{\sin 2\beta} + \mathcal{O}(v^2)$ and h SM-like

⇒ single parameter:

$$\xi = \frac{v^2}{2m_A^2} \sin^2(2\beta) \; [\lambda_1 - \lambda_2 + (\lambda_1 + \lambda_2 - \lambda_3 - \lambda_4 - \lambda_5) \cos 2\beta]$$

$$\sin^2(\beta - \alpha) \approx 1 - \xi^2 \qquad \frac{\cos^2\alpha}{\sin^2\beta} \approx 1 + 2\xi \cot\beta \qquad \frac{\sin^2\alpha}{\cos^2\beta} \approx 1 - 2\xi \tan\beta$$



Lopez-Val, Plehn, Rauch

(iii) MSSM

ϕ	g_u^ϕ	g_d^ϕ	g_V^ϕ
h	c_α/s_β	$-s_\alpha/c_\beta$	$s_{\beta-\alpha}$
H	s_α/s_β	c_α/c_β	$c_{\beta-\alpha}$
A	$\mathrm{ctg}\beta$	$\mathrm{tg}\beta$	0

$$\mathrm{tg}\beta\uparrow \quad \Rightarrow \quad g_u^\phi\downarrow \quad g_d^\phi\uparrow \quad g_V^\phi\downarrow$$

- decoupling limit: $M_A \gg M_Z$: h SM-like

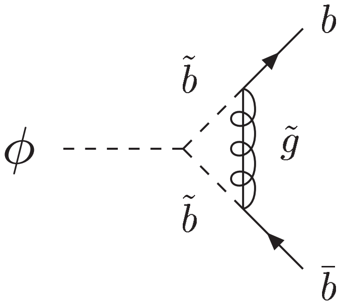
$$\frac{\Gamma_{\mathrm{SUSY}}[h\to VV^*]}{\Gamma_{\mathrm{SM}}[h\to VV^*]} \approx 1 - \frac{m_Z^4 \sin^2 2\beta}{m_A^4}(\cos 2\beta + R_t)^2$$

$$\frac{\Gamma_{\mathrm{SUSY}}[h\to uu]}{\Gamma_{\mathrm{SM}}[h\to uu]} \approx 1 + \frac{4m_Z^2 \cos^2\beta}{m_A^2}(\cos 2\beta + R_t)$$

$$\frac{\Gamma_{\mathrm{SUSY}}[h\to dd]}{\Gamma_{\mathrm{SM}}[h\to dd]} \approx 1 - \frac{4m_Z^2 \sin^2\beta}{m_A^2}(\cos 2\beta + R_t)$$

$$R_t \approx \frac{3(g^2+g'^2)}{16\pi^2\sin^2\beta}\frac{m_t^4}{m_Z^4} \left[\log\frac{m_{\tilde t_1}m_{\tilde t_2}}{m_t^2} + (A_t - \mu\cot 2\beta)\frac{A_t-\mu\cot\beta}{m_{\tilde t_1}^2 - m_{\tilde t_2}^2}\log\frac{m_{\tilde t_1}^2}{m_{\tilde t_2}^2}\right.$$
$$\left. + (A_t^2 - \mu^2 - 2A_t\mu\cot 2\beta)\left(\frac{A_t-\mu\cot\beta}{m_{\tilde t_1}^2 - m_{\tilde t_2}^2}\right)^2\left(1 - \frac{m_{\tilde t_1}^2 + m_{\tilde t_2}^2}{m_{\tilde t_1}^2 - m_{\tilde t_2}^2}\log\frac{m_{\tilde t_1}}{m_{\tilde t_2}}\right)\right]$$

- Δ_b corrections to bottom Yukawa couplings:

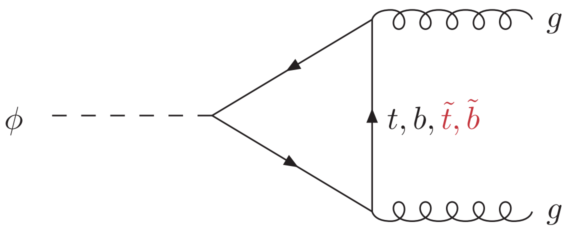


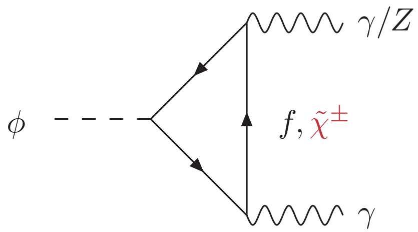
$$+ \cdots \qquad \propto \frac{\alpha_s}{\pi} \frac{m_{\tilde{g}} \mu \, \mathrm{tg}\beta}{m_{\tilde{b}}^2}$$

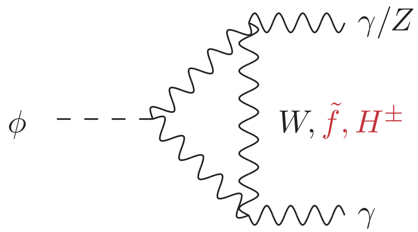
Hall, . . .
Carena, . . .
Nierste, . . .
Guasch, . . .
etc.

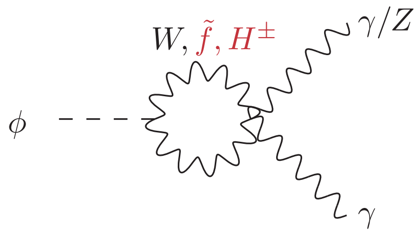
$\Rightarrow g_{d,s} \neq g_b$ [violations also possible in lept. sector]

- loop effects in $\phi \to gg, \gamma\gamma, Z\gamma$:









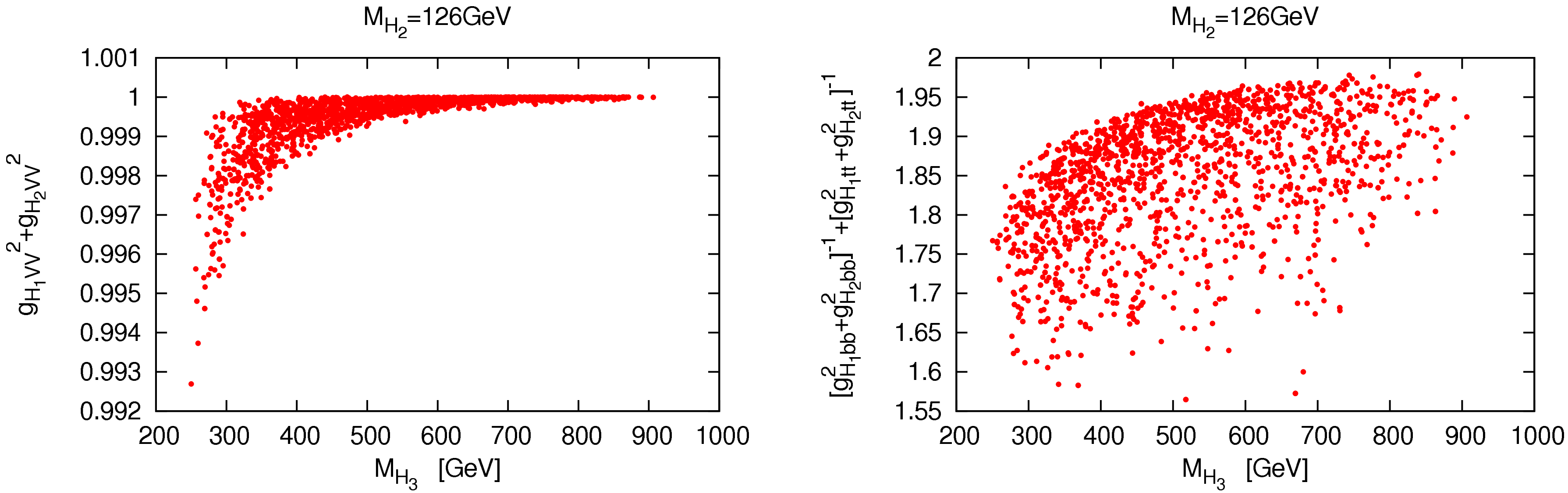
(iv) NMSSM

- additional Higgs singlet → 7 Higgs bosons [neutralinos]: $H_{1,2,3}, A_{1,2}, H^{\pm}$

- iff 3 Higgses found: MSSM? NMSSM? → sum rules:

$$\sum_{i=1}^{3} g^2_{H_iVV} = 1 \qquad\qquad \frac{1}{\sum_{i=1}^{3} g^2_{H_itt}} + \frac{1}{\sum_{i=1}^{3} g^2_{H_ibb}} = 1$$

e.g. $H_{1,2}, A_1$ discovered, H_2 SM-like:



⇒ sum rules useful for consistency tests

Englert, Freitas, Mühlleitner,. . .

$g_i = g_i^{SM}(1 + \Delta_i) \qquad \Delta_i = \frac{v^2}{\Lambda^2}$

Scenario/framework	LHC	HL-LHC	LC	HL-LC
Higgs portal	0.23	0.28	0.44	0.56
2HDM type-II ($\tan\beta \approx 1$)	0.52	0.58	1.15	1.6
2HDM type-II ($\tan\beta \approx 10$)	0.33	0.36	0.7	1.0
$D = 6$ effective operators:				
hVV	0.78	0.87	2.6	3.3
hff	0.45	0.50	1.0	1.4
hgg contact	0.55	1.1	1.3	1.8
$h\gamma\gamma$ contact	0.15	0.18	0.24	0.36
Strong interactions	0.9	1.1–2.0	2.8–5.1	3.4–5.6
hgg loop effects:				
scalar triplet	0.16	0.31	0.37	0.52
scalar octet	0.39	0.75	0.92	1.3
vector octet	1.8	3.5	4.2	5.8
$h\gamma\gamma$ loop effects:				
scalar triplet	0.15	0.18	0.24	0.36
scalar octet	0.25	0.29	0.39	0.60
vector octet	1.1	1.3	1.8	2.7

Englert, Freitas, Mühlleitner, Plehn, Rauch, S., Walz

IV CONCLUSIONS

- deviations of Higgs couplings: dim6, BSM

- dim6: SILH & non-linear Lagrangians

- systematic extension of SM $\to$ well-defined expansions

- SILH: expansion in $v^2/f^2, E^2/M^2, \alpha_s/\pi, \alpha/\pi$

- non-lin.: expansion in $E^2/M^2, \alpha_s/\pi$

- BSM: mixing effects, loop effects

$\to$ sensitivity to TeV scale already now

BACKUP SLIDES

$$\overline{m}_Q(M_Q) = \frac{M_Q}{1 + \frac{4}{3}\frac{\alpha_s(M_Q)}{\pi}} + \mathcal{O}(\alpha_s^2)$$

$$\overline{m}_Q(\mu) = \overline{m}_Q(M_Q)\frac{c[\alpha_s(\mu)/\pi]}{c[\alpha_s(M_Q)/\pi]}$$

$$c(x) = \left(\frac{9}{2}x\right)^{\frac{4}{9}}\left[1 + 0.895\ x + \mathcal{O}(x^2)\right] \qquad \text{for } M_s < \mu < M_c$$

$$c(x) = \left(\frac{25}{6}x\right)^{\frac{12}{25}}\left[1 + 1.014\ x + \mathcal{O}(x^2)\right] \qquad \text{for } M_c < \mu < M_b$$

$$c(x) = \left(\frac{23}{6}x\right)^{\frac{12}{23}}\left[1 + 1.175\ x + \mathcal{O}(x^2)\right] \qquad \text{for } M_b < \mu < M_t$$

$$
\begin{aligned}
\bar{g}_Q(M_H) &= \sqrt{2}\,\frac{\overline{m}_Q(M_H)}{v} \\
\bar{g}_Q(M_Q) &= \sqrt{2}\,\frac{\overline{m}_Q(M_Q)}{v} \\
g_Q^{pole} &= \sqrt{2}\,\frac{M_Q}{v}
\end{aligned}
$$

$$
\Gamma(H \to Q\bar{Q}) = \bar{g}_Q^2(M_H)\,\frac{3M_H}{16\pi}\left\{1 + \frac{17}{3}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\}
$$

$$
\begin{aligned}
\Gamma(H \to Q\bar{Q}) &= \bar{g}_Q^2(M_Q)\,\frac{3M_H}{16\pi}\left\{\frac{c[\alpha_s(M_H)/\pi]}{c[\alpha_s(M_Q)/\pi]}\right\}^2\left\{1 + \frac{17}{3}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\} \\
&= \left(g_Q^{pole}\right)^2\frac{3M_H}{16\pi}\left\{\frac{1}{1+\frac{4}{3}\frac{\alpha_s(M_Q)}{\pi}}\,\frac{c[\alpha_s(M_H)/\pi]}{c[\alpha_s(M_Q)/\pi]}\right\}^2\left\{1 + \frac{17}{3}\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\}
\end{aligned}
$$

$$
\begin{aligned}
\Gamma(H \to Q\bar{Q}) &= \frac{3G_F M_H}{4\sqrt{2}\pi}\overline{m}_Q^2(M_Q)\left\{1 + \left[\frac{17}{3} - 2\log\frac{M_H^2}{\overline{m}_Q^2(M_Q)}\right]\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\} \\
&= \frac{3G_F M_H}{4\sqrt{2}\pi}M_Q^2\left\{1 + \left[3 - 2\log\frac{M_H^2}{M_Q^2}\right]\frac{\alpha_s}{\pi} + \mathcal{O}(\alpha_s^2)\right\}
\end{aligned}
$$